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An analysis on a two-stage cascade thermoelectric cooler for electronics cooling applications

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ABSTRACT

This paper presents a comprehensive analysis of a novel two-stage cascade thermoelectric cooler (TTEC). The novel TTEC may be simply formed by joining short-legged thermoelectric couples in cascade, which has advantages of no interstage electrical insulating materials, compact and easy-fabricated structure, and using only one operating power. An analytical model taking into account the allocation of the total input current between the two stages of the TTEC is developed and the performance characteristics are investigated in detail. Especially, the allocation ratio of thermoelectric couple leg length which maximizes the TTEC COP at a specified condition are discussed. The analysis results indicate that such a cascade TTEC can greatly improve the operating temperature difference and be in theory more efficient than a single-stage thermoelectric cooler under most circumstances. It is also revealed that the allocation ratio of thermoelectric couple leg length plays an important role in determining TTEC thermal performance. Overall, the presented TTEC may show its promise in the future electronics cooling applications.

Analyse d'un refroidisseur thermoélectrique biétagé en cascade pour des applications de refroidissement de l'électronique

Mots clés : Refroidisseur électronique ; Biétagé ; Modèle analytique ; Refroidissement des systèmes électroniques

1. Introduction

Thermoelectric coolers (TECs) are solid-state refrigerating devices that utilize the Peltier effect to pump heat. Thermoelectric coolers also offer the advantages of compact size, quiet operation, high reliability and exact temperature control, and thus they are widely used as refrigerating devices in many applications including military, aerospace, industrial and commercial areas. In recent years, there has been increased interest in the application of thermoelectric cooler to electronics cooling. De Bock and Icoz (2007) presented a formulation of TEC characterization and its performance evaluation in electronics cooling applications. Russel et al. (2012) compared a hybrid thermal management

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Nomenclature

A	area (m^2)
a,b,c	coefficients of the quadratic equation
COP	coefficient of performance
I	electrical current (A)
K	thermal conductance ($W\ K^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	leg length (m)
$\dot{Q}$	heat transfer rate (W)
R	electrical resistance (Ω)
T	temperature (K)
ΔT	temperature difference (K)
U	voltage drop (V)
R_k	thermal contact resistance ($m^2\ K\ W^{-1}$)

Greeks symbols

α	Seebeck coefficient ($V\ K^{-1}$)
ϕ	ratio of first-stage current to total input current
λ	ratio of first-stage leg length to total leg length
ρ	electrical resistivity (Ω m)
ρ_c	electrical contact resistance ($\Omega\ m^2$)

Subscripts

1	first stage, first root
2	second stage, second root
c	cold side
corr	corresponding
h	hot side
m	intermediate
max	maximum value
n	n-type semiconductor elements
p	p-type semiconductor elements
t	total

configuration to a heat pipe based passive system and an only TEC system. Martínez et al. (2011) proposed a novel concept of thermoelectric self cooling, which can be introduced as the cooling and temperature control of a device using thermoelectric technology without electricity consumption. Zhang et al. (2010) analyzed the TEC performance in the high power electronic package cooling.

However, the limitation of present TEC systems lies in their low system COP as the advance in thermoelectric material has been marginal in recent years. Thus, the developments in configuration and optimization design for a thermoelectric device are of great importance (Shen et al., 2012; Wang et al., 2012; Zhang, 2010; Zhou and Yu, 2012). Lineykin and Ben-Yaakov (2007) proposed a universal graphical method for the optimization design of TEC-based active cooling systems. Huang et al. (2010) verified that the thermal performance of the conventional water-cooling device can be effectively enhanced by integrating it with a TEC when the heat load is below 57 W. In a Comprehensive System-Level study on the electric cooling, Taylor and Solbrekken (2008) found that it is possible to design a TE solution that will both maximize the COP and minimize the junction temperature.

In previous studies, most attempts have focused on the conventional single-stage TECs application for electronics cooling. However, it is well known that the maximum temperature difference provided by a single-stage TEC (STEC) is limited. For certain electronic instruments, such as low power semiconductor diodes and lasers, single-element IR-detectors, bolometers and other electro-optic (EO) instruments which require a typical temperature range of 170–300 K, conventional single-stage TECs are not able to offer required cooling temperature. In this case, multistage or cascaded TECs are useful for these electronics cooling applications (Rowe, 2005). Application of multistage or cascaded TECs has been widely investigated (Karimi et al., 2011; Razani et al., 2012). Semeniouk and Berzverkbov (1997) developed a cascade TEC model with consideration of interstage thermal resistance. They found that the losses at interstage thermal resistance can predominate over other kinds of losses and the optimization on the interstage substrate permits to receive considerable increase in TEC efficiency. Yang et al. (2004) designed and analyzed multistage coolers by focusing on the optimization of the maximum temperature difference. Hwang et al. (2009) designed a planar (two-dimensional) multistage micro which is compatible with microelectromechanical system (MEMS) fabrication. Nevertheless, its cooling performance is reduced compared to that of a pyramid (three-dimensional) design, due to a technical limit on TE film thickness. In these studies, various efforts have been devoted to enhancing the cooling design and performance for multistage or cascaded TECs.

Overall, multistage or cascaded TECs are finding wide application in cooling electronic and optoelectronic components. In addition to the studies outlined above, research should be further conducted to develop better multistage or cascaded TECs. Thus, the objective of the present study is to demonstrate a possible two-stage cascade thermoelectric cooler (TTEC) for electronics cooling applications which has no interstage electrical insulting materials and need only one power to operate. An analytical model taking into account the allocation of the total input current between the two stages of the TTEC is derived to evaluate its thermal performance. The effects of the main parameters on the TTEC performance and optimum design are then discussed in the analysis.

2. TTEC unit and mathematical model

Fig. 1 illustrates a fundamental TTEC unit. In this unit, the thermoelectric couple in each stage is composed of a pair of p- and n-type semiconductor elements. The p-type and n-type semiconductor elements of the first stage (closer to hot side) and the second stage are placed on opposite sides, and the two stages are connected thermally in series and electrically in parallel by only copper metal strips. There are three junctions by regarding the unit as a whole element, the hot junction (the hot junction of the first stage), the intermediate junction (the cold junction of the first stage or the hot junction of the second junction) and the cold junction (the cold junction of the second stage). In this case, only a couple of electrodes, i.e. intermediate metal strips, are needed between thermoelectric

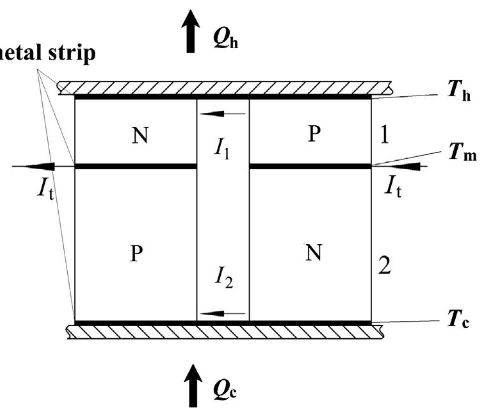

Fig. 1 – Schematic diagram of a TTEC unit.

couples, and no insulating materials are added between the two stages. On the one hand, the presented element does not introduce extra non-conventional structures. On the other hand, the results of decreasing thermoelectric couple leg length down to 0.2 mm with a TEC retaining performance at an acceptably high level has been reported and the possibilities of the bulk technology, which is gradually approaching the sub-millimeter level, have not yet been exhausted (Rowe, 2005). Thus, this configuration may be easily constructed by thermally cascading commercial thermoelectric couples. It should be noted that each thermoelectric couple has the same cross-sectional area, but the different leg length, so that the first stage can completely pump the heat dissipated by the second stage. This is because the heat pumping capacity of each stage is inversely proportional to leg length. In comparison with the conventional pyramid configuration, the presented TTEC unit designs carry inherent advantages in fabricating a TTEC module. First of all, both the additional interstage thermal resistances and the heat leakage can be reduced compared with that of a conventional pyramid-styled configuration. In addition, owing to the compact structure of the presented TTEC unit, more units can be connected electrically in series and thermally in parallel to further fabricate a TTEC module. Lastly, there is only one power needed to operate such a TTEC module.

As well known, the standard equations of a TEC performance can be found in many different references (Chen and Snyder, 2013; Mitrani et al., 2009; Rowe, 2005). For a basic two-stage cascade TEC unit, due to neglecting any contact resistances, interstage thermal resistance and the heat leakage to ambient surroundings, there is no temperature difference in the intermediate junction. The heat released at hot junction $\dot{Q}_h$ and the heat absorbed at the cold junction $\dot{Q}_c$ can be, respectively, written as

$$\dot{Q}_h = \alpha_1 I_1 T_h - K_1(T_h - T_m) + \frac{1}{2}R_1 I_1^2 \tag{1}$$

$$\dot{Q}_c = \alpha_2 I_2 T_c - K_2(T_m - T_c) - \frac{1}{2}R_2 I_2^2 \tag{2}$$

where subscripts 1 and 2 refer to the first and second stage, respectively. I_1, I_2 are the electrical currents. T_h, T_m and T_c are the temperatures of the hot, intermediate, and cold junctions, respectively. The thermoelectric couples leg length L_1, L_2, the cross-sectional area A, the total Seebeck coefficients, α_1, α_2 the serial electrical resistances, R_1, R_2, and the parallel thermal conductances, K_1, K_2, are given by

$$\alpha_1 = |\alpha_{n1}| + |\alpha_{p1}|, \quad \alpha_2 = |\alpha_{n2}| + |\alpha_{p2}| \tag{3}$$

$$\begin{aligned} K_1 &= (k_{n1} + k_{p1})\frac{A}{L_1},\ K_2 = (k_{n2} + k_{p2})\frac{A}{L_2}, \\ R_1 &= (\rho_{n1} + \rho_{p1})\frac{L_1}{A},\ R_2 = (\rho_{n2} + \rho_{p2})\frac{L_2}{A} \end{aligned} \tag{4}$$

where the Seebeck coefficients, the thermal conductivities and the electrical resistivities of p-type and n-type semiconductor elements are temperature-dependent (Rowe, 1995) and they are calculated according to the corresponding average temperature of the two stages (i.e. $(T_h + T_m)/2$ and $(T_m + T_c)/2$) (Hwang et al., 2009; Mitrani et al., 2009; Rowe, 2005).

The total input current I_t and the total leg length L_t can be written as

$$I_t = I_1 + I_2,\ L_t = L_1 + L_2 \tag{5}$$

In order to facilitate the analysis, we introduce the ratio of first-stage current to total input current ϕ and the ratio of first-stage leg length to total leg length λ as

$$\varphi = \frac{I_1}{I_t},\ \lambda = \frac{L_1}{L_t} \tag{6}$$

To satisfy the heat balance between the two stages, the heat absorbed by the first stage $\dot{Q}_m$, which equals to the heat dissipated from the second stage, is expressed as

$$\begin{aligned} \dot{Q}_m &= \alpha_1 I_1 T_m - K_1(T_h - T_m) - \frac{1}{2}R_1 I_1^2 \\ &= \alpha_2 I_2 T_m - K_2(T_m - T_c) + \frac{1}{2}R_2 I_2^2 \end{aligned} \tag{7}$$

From Eq. (7) we can obtain the expression of T_m as

$$T_m = \frac{K_1 T_h + K_2 T_c + \frac{1}{2}R_1 I_1^2 + \frac{1}{2}R_2 I_2^2}{\alpha_1 I_1 - \alpha_2 I_2 + K_1 + K_2} \tag{8}$$

The voltage drop applied to the unit to overcome the Seebeck effect and the resistive voltage drop is given by

$$U = \alpha_1(T_h - T_m) + \varphi R_1 I_t = \alpha_2(T_m - T_c) + (1 - \varphi)R_2 I_t \tag{9}$$

And from Eq. (9), ϕ can be written in the form

$$\varphi = \frac{R_2 I_t + (\alpha_1 + \alpha_2)T_m - \alpha_1 T_h - \alpha_2 T_c}{R_1 I_t + R_2 I_t} \tag{10}$$

Substituting Eq. (8) into Eq. (10), we obtain a quadratic equation with respect to ϕ as

$$a\varphi^2 + b\varphi + c = 0 \tag{11}$$

where a, b, c are the coefficients of the quadratic equation and are expressed as follows

$$a = \frac{1}{2}(\alpha_1 + \alpha_2)I_t^2(R_1 + R_2) \tag{12}$$

$$b = (\alpha_1 + \alpha_2)I_t(\alpha_1 T_h + \alpha_2 T_c) + I_t(R_1 + R_2)(K_1 + K_2 - I_t\alpha_2) \tag{13}$$

$$\begin{aligned} c = {} & (K_1 + K_2 - I_t\alpha_2)(T_c\alpha_2 + T_h\alpha_1 - I_t R_2) \\ & - (\alpha_1 + \alpha_2)\left(\frac{1}{2}R_2 I_t^2 + K_2 T_c + K_1 T_h\right) \end{aligned} \tag{14}$$

During the calculation processes, we found that one root of the quadratic equation always has a negative value. Thus, we consider the other positive root as the valid solution

for the quadratic equation. When the parameters such as T_h, T_c, I_t, L_t and λ are specified, the corresponding T_m and ϕ can be solved by the iterative method and the coefficient of performance of the basic unit can then be obtained

$$\mathrm{COP} = \frac{\dot{Q}_c}{\dot{Q}_h - \dot{Q}_c} \tag{15}$$

Because the electrical and thermal contact resistances between the TE legs and the copper strips could usually affect the performance of a thermoelectric device in short leg length situations, we will examine the influences of the interfacial resistances on the presented TTEC in a separate discussion part. When the two contact effects are taking into account, the serial electrical resistances, R_1, R_2, and the parallel thermal conductances, K_1, K_2 can be expressed respectively as (Rowe, 2005)

$$R_1 = \frac{2\rho_1 l_1}{A} + \frac{4\rho_c}{A},\ R_2 = \frac{2\rho_2 l_2}{A} + \frac{4\rho_c}{A} \tag{16}$$

$$K_1 = \frac{1}{\frac{l_1}{2\lambda_1 A} + \frac{2R_k}{2A}},\ K_2 = \frac{1}{\frac{l_2}{2\lambda_2 A} + \frac{2R_k}{2A}} \tag{17}$$

where ρ_c and R_k are electrical and thermal contact resistances, respectively.

3. Results and discussion

In the following simulations, the typical Bi_2Te_3 based semiconductors are selected as thermoelectric materials of TTEC. For thermoelectric couples, the cross-sectional area is assumed to be $A = 2.8 \times 2.8 \times 10^{-6}\ \mathrm{m}^2$, the thermoelectric element legs are set in the range from 4×10^{-3} to 6×10^{-3} m.

Fig. 2 shows COP, $\dot{Q}_c$ (a) and T_m (b) of TTEC plotted as a function of total input current I_t when L_t, T_h are set to 5×10^{-3} m, 313 K, respectively. T_c is specified to a relatively lower temperature of 228 K at which STEC can no longer work. The λ is set to 0.3 in Fig. 2 (a) and is varied from 0.1 to 0.4 in Fig. (b). Similar to STEC, TTEC can also achieve a maximum COP and $\dot{Q}_c$ under a given operating condition. However, there exists an intermediate temperature T_m in TTEC. When the temperatures of the hot and cold junctions and the leg length of the first and second stage are specified, T_m varies as a function of I_t. It is clearly displayed in Fig. 2(b) that the level of the T_m is dominated by λ and smaller λ usually leads to lower T_m over the ranges of I_t. When I_t is specified to maximize $\dot{Q}_c$, T_m of TTEC with λ of 0.3, 0.2 and 0.1 decreases by 6 K, 16 K and 28 K compared to that of TTEC with λ of 0.4, respectively. Similar varying tendency can also be obtained when I_t is set to achieve the maximum COP.

At the given T_c, T_m varies with I_t in a different way when λ is kept at a different value. When λ is specified to 0.1 or 0.2, T_m shows a decreasing tendency at first and then turns to increase after reaching the bottom value as I_t continuously increases. However, when λ is set to 0.3 or 0.4, T_m is observed to rise monotonically. As well known, TECs do not work normally when the input current is lower than a certain value, i.e. a minimum working current. Thus, the drop tendency can not be observed when $\lambda = 0.1$ or $\lambda = 0.2$ in Fig. 2(b) because the I_t corresponding to the minimum T_m is smaller than the minimum working current.

Fig. 3 displays the variations the maximum $\dot{Q}_c$ and the corresponding COP of TTECs and STEC versus T_c. I_t is specified to achieve the maximum $\dot{Q}_c$. When T_c is continuously lowered, both TTECs and STEC suffer from severe performance deteriorations and finally reach their working limits. However, compared to that provided by STEC, the available maximum temperature difference ΔT of TTECs are much greater. The improvements of TTECs with λ of 0.1, 0.3 and 0.5 are 35 K, 21 K and 4 K, respectively. It means that the maximum working

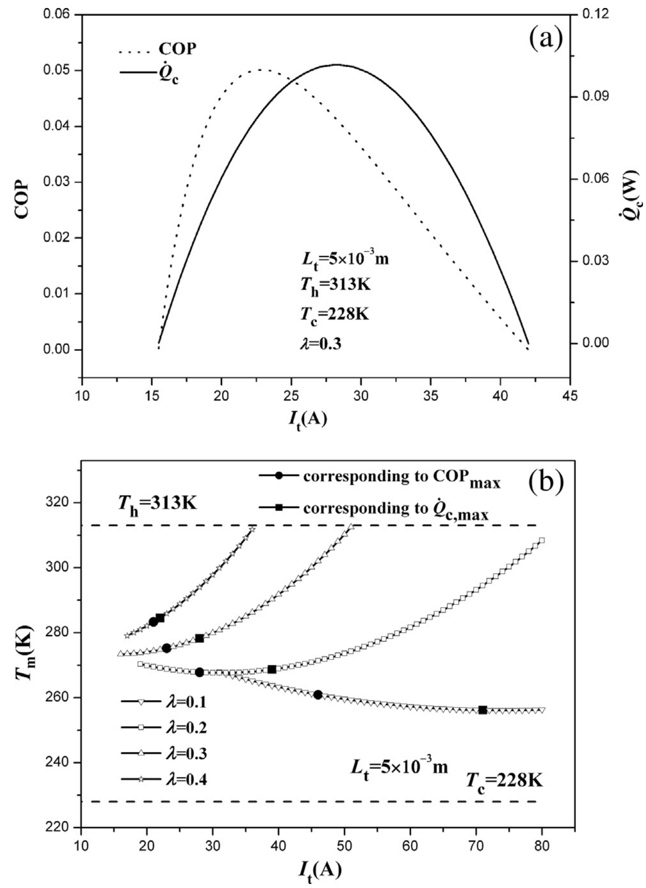

Fig. 2 – (a) – COP and cooling capacity $\dot{Q}_c$ of TTEC versus input total current I_t. (b) – The intermediate temperature T_m of TTEC with various ratios of first-stage leg length to total leg length λ versus input total current I_t.

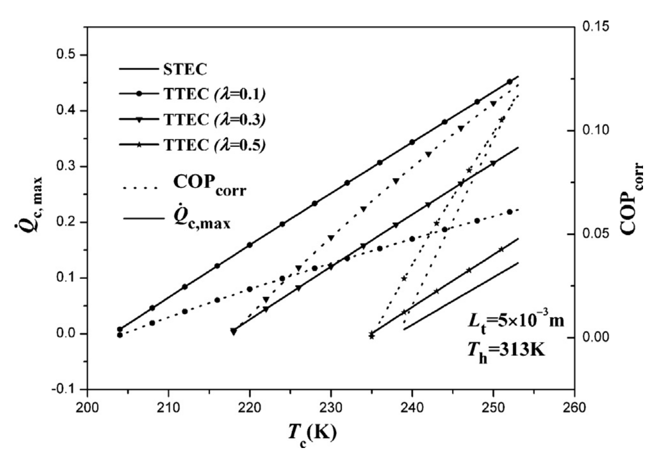

Fig. 3 – The maximum $\dot{Q}_c$ and the corresponding COP of TTEC and STEC versus T_c.

temperature difference ΔT_{max} significantly increases when λ decreases. As presented in Fig. 2(b), TTEC with smaller λ would gain much lower T_m when $\dot{Q}_c$ is maximized and thus enable the second stage to reach a lower T_c.

In Fig. 3, it also reveals that, for a given T_c and L_t, TTEC always achieves greater $\dot{Q}_{c,\ max}$ than that of STEC. Firstly, the first stage of TTEC offers much lower hot junction temperature for the second stage (i.e. T_m), which provides $\dot{Q}_c$ for the whole TTEC at its cold junction. This causes a great performance improvement for the second stage thermal couple. Secondly, as well known, the cooling capacity a thermoelectric cooler can provide is inversely proportional to the thermoelectric couple leg length. In the comparison, the leg length of STEC is specified to equal to the total leg length of TTEC. In this case, the second stage of TTEC has a shorter leg length than that of STEC. This also contributes to the further improvement in $\dot{Q}_{c,\ max}$.

In Fig. 3, it also informs us that $\dot{Q}_{c,\ max}$ show a greatly increasing tendency as λ decreases at a fixed T_c. This phenomenon differs from the comparison between TTEC and STEC. It is dominated by two opposite effects. On the one hand, as mentioned previously, smaller λ leads to lower T_m under the maximum $\dot{Q}_c$ condition when T_c is fixed. It contributes to the improvement in $\dot{Q}_{c,\ max}$. On the other hand, for a given L_t, smaller λ means more leg length inventory is split into the second stage which would make negative effects for increasing $\dot{Q}_{c,\ max}$. The overall outcome is $\dot{Q}_{c,\ max}$ increases significantly as λ decrease for a given L_t.

Fig. 4 shows the effects of λ and L_t on the maximum COP and the corresponding $\dot{Q}_c$ under the given condition. L_t is set to 4×10^{-3} m, 5×10^{-3} m and 6×10^{-3} m, respectively. T_c is fixed at 228 K. Similar to that in Fig. 3, I_t is specified to achieve the maximum COP. It is illustrated that COP_{max} reaches its peak value at a λ of 0.195 under the given condition. A further increased λ would cause a drop in COP_{max} and finally lead to a failure of TTEC. As explained previously, the cooling capacity a TEC can offer is inversely proportional to the leg length. Differing from the conventional pyramid two-stage TEC, the presented TTEC pump the excessive heat dissipated from the second stage by decreasing the leg length of the first stage. Consequently, λ is usually specified less than a certain value to keep heat balance well between the two stages. It is clearly illustrated that L_t has no effects on COP_{max} under a given condition. The phenomenon is similar to the case that COP_{max} of an STEC is only a function of T_h, T_c, and the figure of merit and is independent of the leg length. In the case of $\dot{Q}_{c,\ corr}$, shorter L_t and smaller λ increase the $\dot{Q}_{c,\ corr}$ significantly. The reasons for these variation tendencies are similar to the case of $\dot{Q}_{c,\ max}$.

Fig. 5 illustrates the performance comparison between STEC and TTECs with various λ when I_t is set to maximize COP. As can be seen in the Fig. 5, TTEC with λ of 0.3 improves COP_{max} by 21.3%–102.3% compared to that of STEC when T_c ranges from 263 K to 248 K. The COP_{max} improvement of TTEC with $\lambda = 0.5$ under the same condition is from 4.6% to 20.9%. TTEC with proper λ, such as 0.3, always offers much greater COP_{max} than that of STEC in the operating temperature range that STEC works well. Moreover, the enhancement increases rapidly as T_c decreases. It indicates that the presented TTEC can be applied in temperature ranges not only that STEC could not work but also that STEC offers good performance. When λ is specified smaller, such as 0.1, TTEC could provide greater ΔT but have no advantages in COP_{max} when T_c is greater than 251 K. The $\dot{Q}_{c,\ corr}$ shows the similar variation tendencies compared to the case of $\dot{Q}_{c,\ max}$ when T_c decreases. In summary, the leg length inventory should be divided properly by an overall consideration according to specific application requirements.

Since the electrical and thermal contact resistances between the TE legs and the copper strips may cause performance degradation of all the TECs in the extremely short leg length situation, the two interfacial resistances are taken into account in the model and the results are illustrated in Fig. 6. As the values an electrical contact resistance in a TEC are reported to be of order of 10^{-10}–$10^{-11}\Omega m^2$ in the literature (Astrain et al., 2010; Rowe, 2005; Yang et al., 2004), we select a conservative one of $10^{-10}\Omega m^2$. For the case of a thermal contact resistance, a conservative value is also selected of $10^{-7} m^2KW^{-1}$ (Da Silva and Kaviany, 2004). It is illustrated that, the performance deterioration caused by the electrical and thermal contact resistance are very slightly in the presented case. When $\lambda = 0.1$, the influences of the two contact effects on $\dot{Q}_{c,\ corr}$ are obviously greater than that of the cases $\lambda = 0.3$ and $\lambda = 0.5$. As well known, the impacts of the electrical and thermal contacts significantly increase when the TEC leg length is less than a certain value. Yang et al. (Yang et al., 2004) reported that for a leg length larger than 30 μm and an electrical contact resistance selected of the order of $10^{-11}\Omega m^2$, the degradation will be less than 7%.

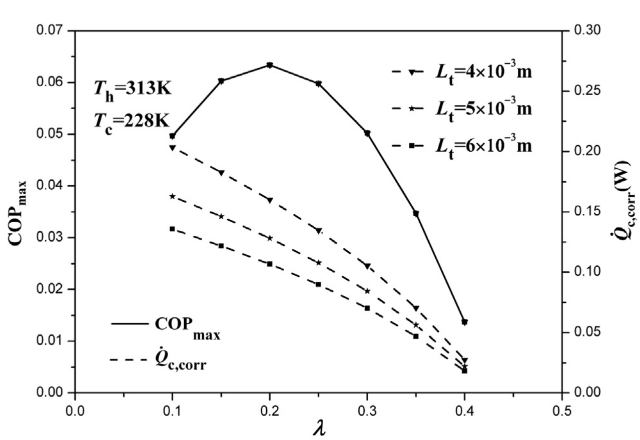

Fig. 4 – The maximum COP and the corresponding $\dot{Q}_c$ plotted as a function of λ.

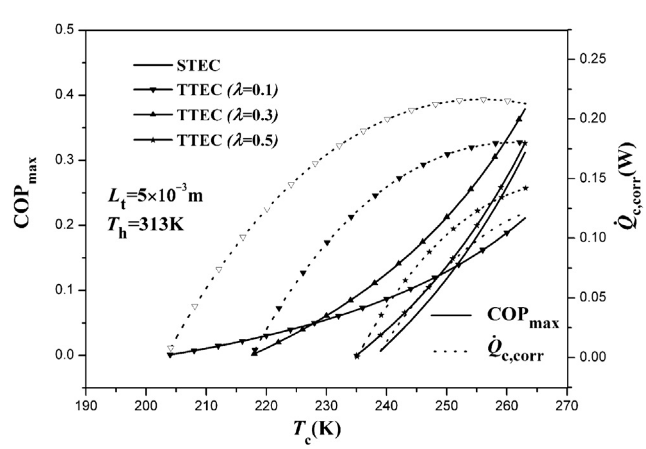

Fig. 5 – The maximum COP and the corresponding $\dot{Q}_c$ plotted as a function of T_c.

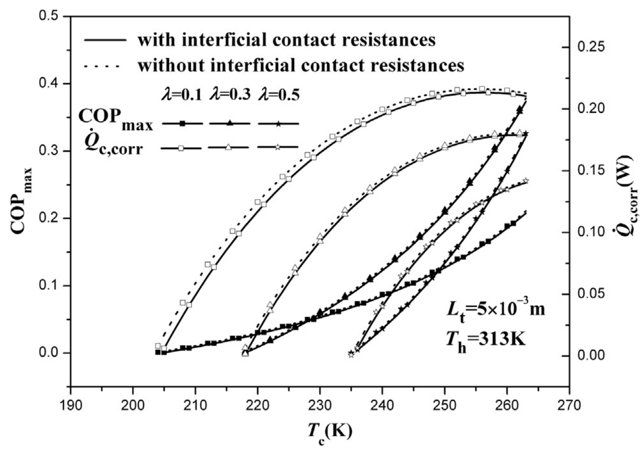

Fig. 6 – The influences of the interfacial resistances on the maximum COP and the corresponding $\dot{Q}_c$.

In another literature (Rowe, 2005), it is reported that, for traditional bulk configuration when the TE leg length exceeds 0.1 mm, these unfavorable factors would not become predominate. Thus, the greater discrepancy when $\lambda = 0.1$ can be accounted for by the much shorter first stage leg length and the obtained results agree with the conclusions in literature.

4. Conclusions

A two-stage cascade TEC is presented and the corresponding analytical model is developed. The presented TTEC has a more compact structure and may be easily fabricated. Similar to conventional pyramid-styled two-stage TEC, the presented TTEC can also provide a relatively high temperature difference. For the case of leg length division, on the one hand, a smaller λ provides a relatively lower T_m and then results in greater operating temperature difference and cooling capacity. On the other hand, a too small λ leads to COP deterioration when T_c is relatively high and properly split leg length ratio contributes to maximizing the COP_{max}. Therefore, a comprehensive consideration should be taken for the specific application circumstance. Furthermore, a TTEC with a proper λ also shows significant performance improvements throughout the whole T_c range of the STEC.

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